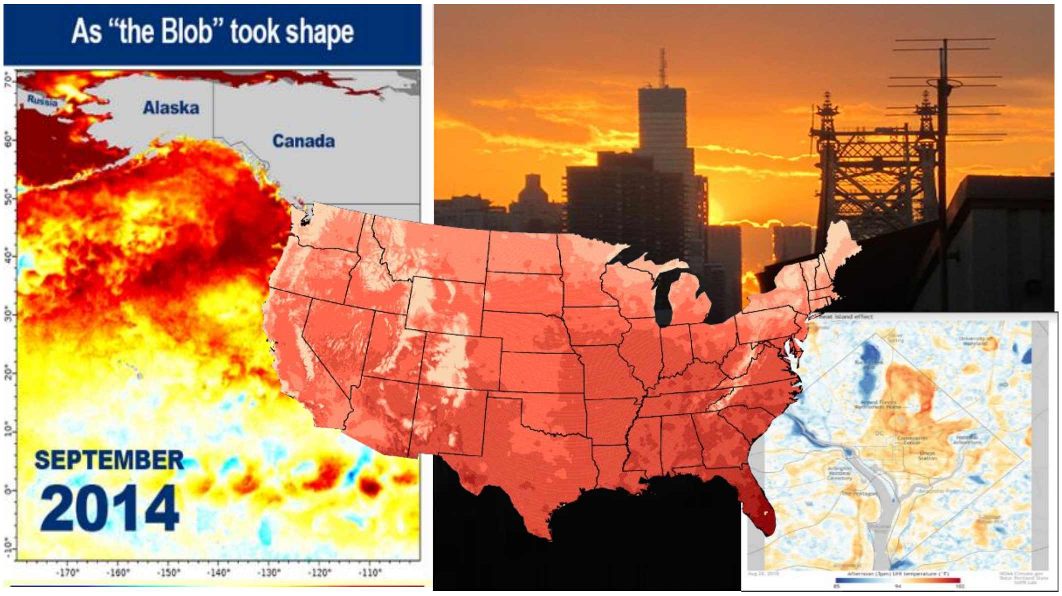
Earth System Science and Modeling Division: Extreme Heat Workshop



Climate Research to Enhance Resilience to Extreme Heat

Aligning research priorities with stakeholder needs

November 2019, Silver Spring, MD

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Workshop Background

Extreme heat events impact communities across the U.S. and are expected to increase in frequency and intensity in the future (NCA4 2018) and result in negative impacts for multiple societal sectors - human health, agriculture and managed lands, fisheries and the blue economy, and energy and transportation. **In response, the Earth System Science and Modeling (ESSM) Division, within the Climate Program Office (CPO) in NOAA/OAR, convened the science and user communities in Silver Spring, MD, November 18-19, 2019, to discuss and identify i) climate information needed to build resilience to extreme heat across societal sectors and ii) research priorities that would address user-identified climate information needs.** The workshop findings and recommendations will inform CPO/ESSM future research directions and funding priorities.

The Workshop included approximately 90 researchers, users and stakeholders from NOAA, university, and other agencies (USDA, CDC), and local government. The workshop was designed to provide information and enhance effective discussions with keynote talks, lightening presentations, breakout sessions, and panel discussions. The ESSM Council and the ESSM program managers met on the following morning to synthesize the discussions and findings from the workshop.

Main outcomes from the Workshop

Key User Perspectives

Critical problems faced by decision-makers in response to extreme heat events were discussed in key impact areas, including Arctic, urban, health, agriculture, forest and range working land, and fisheries. Key needs identified:

- Predicting terrestrial and marine extreme heat events (onset, magnitude, duration, frequency, clustering) with adequate lead-times to enable effective preparedness and response (subseasonal, seasonal to interannual scales), mitigation (interannual to decadal scales) and adaptation (multidecadal, 50-100 years);
- Understanding risks of compound extremes and their multivariate or cascading impacts;
- Improving communication and use of existing climate information (forecast products, tools and data) with users.

Research Gaps

Considering the user needs and existing capabilities in scientific understanding, modeling and observations, the following research gaps are identified:

Modeling

- *Resolution:* Resolutions provided by global, and sometimes regional, climate models are too coarse to meet user needs.

- *Coupling:* Certain features or components (e.g. Air Quality, Urban Canopy) are not incorporated in, or coupled to, the appropriate model to provide needed information (e.g. human exposures to compound extreme heat and air quality impacts in urban areas).
- *Skill:* Information needed by stakeholders often has a low predictive skill, especially on seasonal timescales, which is a major limiting factor for applying climate information to decision making. Current models cannot simulate the US summertime warming holes revealed by observational analyses.

Observations for Process Understanding and Modeling:

- More observations are needed: at-depth soil moisture, urban humidity, snowpack, sea ice cover and thickness, net surface radiation, surface fluxes (land-atmosphere, ocean-atmosphere), subsurface ocean fluxes, ocean advection, vegetation responses to extremes, boundary layer microphysics, and air quality-related variables.
- Coupled multidisciplinary observations are needed on similar scales (e.g. air quality and meteorological variables) under different conditions to improve process understanding and modeling.
- Emerging observation challenges need to be considered. For example, low-cost sensors, citizen science, UAVs, and satellites have the potential to provide many more observations; however, reliability and quality are an important consideration. Continuity and consistency with other historical long-term observational records, in many cases, have not yet been established.

Recommendations for Future Research

Paths forward for the Earth System Science and Modeling Division

ESSM programs including CVP: Climate Variability and Predictability; AC4: Atmosphere Chemistry, Carbon Cycle, and Climate; MAPP: Modeling, Analysis, Predictions and Projections; COM: Climate Observations and Monitoring can work together to consider the following:

- **Enhance understanding of short term and long-term temperature increases (including two core phenomena: Marine heat waves and Terrestrial heat waves), through modeling, analysis, and field campaigns**:
    - Predictability of extremes (onset, duration and intensity), including forcings (GHGs, clouds, aerosols, and landcover changes), large scales atmosphere circulation regimes, and synoptic, sub-seasonal disturbances tied to large scale circulations; or other earth system processes (e.g. land-atmosphere interactions) impacting predictability;
    - Regional responses to climate/global forcings (or mission scenarios);
    - Compound extremes and their multivariate or cascading impacts and feedbacks;
    - Physical-dynamical morphology of marine heat waves, terrestrial heat waves, and areas of pronounced long-term temperature increase (e.g. extreme heating in the Arctic);

- **Improve models and predictive skill, especially at regional scales, through observational and modeling research:**
    - Couple climate models to chemical models on scales relevant to stakeholders for urban applications in order to study multivariable processes important to heat, health, and air quality;

- Increase model resolution for regional/local applications including flexible model grids, downscaling, and AI tools.

Opportunities for ESSM Division and NOAA partnerships.

ESSM Division can work with partners including the Climate Society Interactions Division within the Climate Program Office, the Weather Program Office within OAR, and OAR labs operating observation networks to pursue a subset of outcomes from the Extreme Heat Workshop.

- **CSI and ESSM within CPO could foster transdisciplinary partnerships to increase resilience to extreme heat across societal sectors:**
  - Promote interdisciplinary research and collaboration across the social and physical sciences communities to harness climate modeling for the translation of geophysical variables to actionable metrics;
  - Strengthen sustained collaborative dialogue among climate scientists, policy professionals, and stakeholders to develop useful climate predictions/projections for extremes within the context of how climate information is used and to build user confidence. Emphasis was placed on including transparent information about predictability, limits and biases, and metadata.

- **CPO and the Weather Program Office (WPO) could address needs at the intersection of the S2S and climate timescales:**
  - Use process studies and existing datasets to confront models with observations to assess how models simulate and predict extreme events;
  - Explore forecasts of opportunities of extreme events and long term changes by examining weather-climate interactions associated with certain climate phenomena and analyzing GFDL model large ensembles.

- **CPO in partnership with NOAA labs/centers and other agencies can work to maintain and expand observations to better understand extreme heat processes:**
  - Leverage NOAA-supported observational networks to support collaborations across networks;
  - Sustain and supplement extreme-heat related observations, such as, air quality, health data;
  - Support new observations (including emerging technologies) and field process study efforts to address weaknesses in models specific to applications.

1.0 Introduction

1.1 CPO and ESSM Overview

CPO *advances scientific understanding, monitoring, and prediction of climate and its impacts to enable effective decisions* … and help ... *people, businesses and the environment thrive in the face of climate impacts.* Within CPO, the Earth System Science and Modeling Division works to *understand and predict changes in climate, weather, oceans, and coasts—so people can protect themselves and their property*.

The Earth System Science and Modeling program in the NOAA Climate Program Office is actively building the global and regional scale understanding needed to improve predictions. The program coordinates an array of researchers from federal agencies, national labs, and universities, focusing them on the most pressing climate research necessary to advance NOAA's prediction and other services and applications. ESSM supports research through the following programs:

Climate Variability and Predictability (CVP) Researchers in this program study interactions among the atmosphere, ocean, and land, and how they work together to make weather and climate events. This vital knowledge is needed to improve climate models and predictions so that scientists and society can better anticipate the impacts of future climate variability and change.

Atmospheric Chemistry, Carbon Cycle, and Climate (AC4) Research under this program refines our understanding of chemical processes in the climate system, including emissions, chemistry and deposition of atmospheric trace gases and aerosols. Atmospheric composition and its impacts are studied using various measurement platforms and numerical models.

Modeling, Analysis, Predictions, and Projections (MAPP) This program advances climate and Earth system modeling to improve our ability to predict climate variability. Program outcomes include better simulations of climate conditions on various timescales, improvements in long-term projections of future climate, and improvements in NOAA's climate modeling capabilities.

Climate Observations and Monitoring (COM) This program capitalizes on NOAA's vast observational assets and supports the development of value-add climate datasets and products to advance climate monitoring and climate modeling efforts, as well as better inform future observational efforts.

The ESSM Extreme Heat workshop builds on prior ESSM program investments from the CVP, MAPP, AC4, and COM:

- **Advanced foundational process level understanding and modeling capabilities to represent the earth system and provide high-quality climate information.** CVP has focused on advancing our understanding of how processes, such as the Atlantic Meridional Overturning Circulation, impact regional climate. These investments in process-level understanding, have been instrumental in informing models. In the near future, CVP will make targeted new investments in understanding extremes, including extreme heat following the FY20 NOFO. MAPP has focused on developing a suite of modeling capabilities for a number of applications, including extreme heat. Investments have resulted in advanced subseasonal to seasonal prediction, drought monitoring, and improved reanalyses.

- **Advanced Research to Applications (R2X) in partnership with stakeholders.** AC4 has pioneered efforts to help local governments advance their urban monitoring capabilities for CO_2, an underlying driver of extreme heat events and long term climate changes. Investments have also resulted in valuable data products and insight into air quality impacts from wildfires, an event expected to increase under extreme heat conditions. AC4 is now investing in developing the improved process-level understanding of air quality in urban areas that is critical for accurate predictions in a warmer climate.
- **Developed Indicators to Monitor Change:** COM has focused on the development of several temperature indicators that help communities monitor extremes, using a number of different thresholds. Projects have also resulted in the characterization of changes in the temporal and spatial extent of extreme heat events.

Programs within the Climate Program Office, are also collaboratively working together to address extreme heat and impacts. Four ESSM Division programs (COM, CVP, MAPP, Assessments Program), and the National Integrated Drought Information System (NIDIS) within the CPO have come together to solicit projects for the development of *a Rapid Assessment Capability* within NOAA to quickly understand the causes and mechanisms of extreme heat (land or marine) and drought events. Narrowing in on urban regions, the National Integrated Heat Health Information System (NIHHIS - focused on heat health) and the Communication, Education, and Engagement (CEE) Division are piloting a citizen science campaign to provide high resolution urban heat island maps to support city planning efforts. Together, these research and community engagement efforts highlight the types of investments CPO has made in strengthening the end-to-end pathway of climate research to decision-support to advance the Nation's resilience to extreme heat.

1.2 Workshop overview

Extreme heat events impact communities across the U.S., while marine heat waves impact fisheries and the blue economy. Heat waves, land or marine, are expected to increase in frequency and intensity in the future (NCA4 2018) and result in negative impacts for multiple societal sectors - human health, agriculture and managed lands, fisheries and the blue economy, energy and transportation, etc. **In response to the increasing risks of extreme heat impacts, the Earth System Science and Modeling Division, within the Climate Program Office in OAR, convened the science and user communities to discuss and identify i) climate information needed to build resilience to extreme heat across societal sectors and ii) research priorities that would address user-identified climate information needs.**

Building on CPO programs' past, current, and planned activities, and complementing the range of operational products and services NESDIS and NWS provide to support the public, the Workshop included approximately 91 in-person participants with 6-12 participating remotely. NOAA or NOAA affiliates represented ~55% of the participants and included the OAR, NWS, and Fisheries line offices. University scientists represented approximately ~35% of the participants. The remaining ~10% of participants were from other agencies (USDA, CDC), local government (NYC Mayor's Office) or organizations such as USGCRP and CLIVAR. The format of the workshop was designed to provide information and enhance effective discussions with keynote talks, lightening talks (Presentation Slides), breakout sessions and panel discussions.

Presentations and discussion evolved around two core phenomena: marine heat waves (MHW) and terrestrial heat waves (THW) including urban heat island effects. Discussion on risk and impacts from MHWs centered around sustainability and management of marine ecosystems. Discussion on risk and impacts on THWs centered around urban heat waves with particular emphasis on human health impacts of both extreme heat and air quality of large urban centers, and impacts on coupled coastal and rural human-natural systems with emphasis on agriculture. Special emphasis was placed on so-called compound events and cascade events that refer to extreme events that occur respectively at the same time or in sequence (e.g. THW, wildfires, and flash-droughts).

On the first day of the workshop (*user perspectives on impacts of extreme heat*), the need to predict extreme heat events (onset, magnitude, duration, frequency, clustering) with adequate lead-times to enable effective preparedness and response (subseasonal, seasonal to interannual scales), mitigation (interannual to decadal scales) and adaptation (multidecadal , 501-100 years) was highlighted by stakeholders. A consensus emerged on the need for maintaining collaborative dialogue among climate scientists and policy analysts, managers,etc, which would aim to develop a common understanding of climate phenomena associated with extreme heat toward a shared vision for useful climate predictions at multiple scales. On the second day (*current research capabilities, needs, and gaps)*, the focus was on current modeling and observational capabilities within ESSM programs to assess the predictability of extreme heat risk, including compound and cascade events. Discussions focused on using strategies and metrics that would meet the needs of the various sectors, while advancing climate science and understanding of extreme heat phenomena. The ESSM Council and the ESSM program managers met on the following morning to synthesize the discussions and findings from the workshop.

Participants at the ESSM Workshop. Photo Credit: Courney Byrd.

2.0 User Perspectives

2.1 Keynote Talks

2.1.1 Health, Shubahyu Saha;
Centers for Disease Control and Prevention (Presentation Slides)

The Interagency collaboration between the National Oceanic and Atmospheric Administration (NOAA) and Centers for Disease Control (CDC) has been key in improving public health preparedness to extreme heat. The collaborations have ranged from (i) translating complex climate data for public health practitioners, (ii) analyzing linked temperature and health data to identify sub-optimal temperature range for public health, and (iii) disseminating real-time information on health outcomes associated with exposure to extreme heat. Climate data from the National Center for Environmental Information (NCEI) has been converted to county-level estimates and made freely available on the CDC's Environmental Public Health Tracking Network data portal. This has empowered local health agencies to assess and communicate the health risks associated with the local temperature profile in a changing climate. Epidemiologic analysis of linked, high resolution temperature and health data has improved our understanding of the temperature range that imposes the largest health burden for specific jurisdictions. National Weather Service (NWS) and CDC are collaborating to incorporate this epidemiologic information in recalibrating heat health warnings. Under the auspices of the National Integrated Heat Health Information System (NIHHIS), real-time health data from the CDC's National Syndromic Surveillance Platform (NSSP) is being used in conjunction with temperature data from NOAA to create a prototype of a web service. Refinements to this web service will provide critical situational awareness for public health agencies to launch timely response efforts and minimize the adverse impacts from extreme heat.

2.1.2 Extreme Heat Impacts on Working Lands, Steve McNulty;
United States Department of Agriculture (Presentation Slides)

Agriculture, forest and range working land are currently being impacted by extreme heat, these impacts are expected to increase in the coming years. Not only extreme high daytime temperatures, but also extreme highly low temperatures will cause a host of negative environmental impacts at multiple temporal spatial scales including; early flower blooming followed by frost, a lack of overwinter chill hours leading reduced fruit set, high nighttime temperatures that reduce grain yield, increase wildfire risk and severity, and an increase in detrimental insects and diseases on working lands. Extreme heat will also directly impact the resilience of working lands through increased hurricane strength, and increased ecosystem water use, among other issues. Adaptive management practices need to be developed and more universally employed to offset some of the negative consequences of increasing extreme heat.

2.1.3 Ocean Heat Waves and Fisheries, Mike Jacox and Toby Garfield
NOAA Earth System Research Laboratory; NOAA Fisheries Southwest (Presentation Slides)

Marine heatwaves (MHW) have gained increased attention in recent years as several notable events around the globe have disrupted ocean ecosystems as well as the economies and communities that rely on them. Ecological impacts have been wide-ranging, including reduced primary and secondary production, bleaching and/or mortality of corals and seagrass beds, dramatic range shifts of marine species, altered composition of marine communities, harmful algal blooms and consequent toxicity of shellfish and other species, declines in commercial fish species, and unusual mortality events of marine mammals. A number of fisheries have been affected by these ecological impacts; for example, the 2013-2016 NE Pacific MHW led to fishery disaster declarations for Pacific sardine, red sea urchin, Dungeness crab, and multiple species of salmon along the US west coast. In some cases, effects resulted from complex and unexpected interactions. In 2015-16 the compression of productive nearshore habitat, combined with the closure of the Dungeness crab fishery due to a harmful algal bloom, led to increased interactions with whales when the crab fishery was ultimately opened late, leading to record whale entanglements. In the Gulf of Maine in 2012, a MHW led to lobster landings much earlier and in higher numbers than normal. While one might expect the increased landings to be a welcome surprise, the timing and quantity of landings overwhelmed the processing chain, drove prices down. These events demonstrate the need to expand our understanding of MHW and their impacts and to develop management strategies to cope with these events, including not just adverse effects on existing fisheries but also novel opportunities resulting from, for example, expansion of tropical species' ranges into U.S. waters.

2.1.4 Other Topics

Speakers from the NYC Mayor's Office of Resiliency (Kizzy Charles-Guzman) and the National Weather Service (Jon Gottschalck, [Presentation Slides]) also presented on Extreme Heat Impacts to the urban environment and NOAA products and stakeholder requirements, respectively. Abstracts are not available.

Mike Jacox from NOAA Fisheries and OAR presents work on Marine Heat Waves. Photo Credit: Courtney Byrd.

2.2 Breakout Group Discussion

Extreme Heat and Health Discussions led by chair, Juli Trtanj. Photo credit: Courtney Byrd.

2.2.1 Health

Chair: Juli Trtanj
Rapporteur: Hunter Jones

Critical Problems: The discussion acknowledged the challenges of direct (mortality and morbidity) and indirect impacts (e.g. water-borne, vector-borne, food security, air quality, CDC's One Health initiative) of extreme heat on health and that these impacts occur on different timescales (days to months). Needed intervention strategies would differ by stakeholder group and by region. Regions are experiencing different direct and indirect impacts. For example, in urban areas, city infrastructure's resilience to extreme heat (e.g. the future of the electric grid, water resources, housing, transportation) is an important consideration. In Alaska and the Arctic, direct impacts are less of a concern, rather Harmful Algal Blooms, Wildfires, and increased mean temperatures exacerbate air quality, economic livelihood (tourism), and food security concerns.

Climate Information Needs: Overall, there is a need to balance precision and utility. For example, sometimes qualitative information is valued by stakeholders (e.g. exact number of malaria cases versus general knowledge of a peak malaria season). There is a need to understand cause and effect relationships to improve our knowledge of health impacts that have temporal lag times of 2-3 months, and to answer questions such as - *what thresh-holds make a city uninhabitable?*. Understanding the cause and effect relationships underlying indirect impacts is essential for the implementation of mitigation and adaptation strategies. We need to better connect extreme events and their preventative steps to predicted impact. There is a lack of knowledge on the co-benefits, effectiveness, and cost of intervention strategies for extreme heat.

There is a need for more high resolution data and observations to better understand cause and effect relationships (e.g. Radiation, wind, temp, humidity, tree cover and ecosystem/soil moisture), as well as studies that link extreme heat events to health and human physiology studies. Some opportunities to explore data and observations via citizen science include engaging with CoCoRaHS, citizen science organizations, the private sector (e.g. co-creating apps to monitor personal heat exposure).

- There is a need to understand the range of changes of variance of mean temperature.
- Humidity is an important variable for health and it is not well understood in present climate modeling.
- There is a need to better understand why it has been hot in some places and not others, and how land-use change (e.g. irrigation practices) impacts regional temperatures.

2.2.2 Air Quality

Chair: Greg Frost
Rapporteur: Todd Christenson

Critical Problems: Before CPO/ESSM goes much further in considering what are the critical problems for decision makers with respect to air quality (AQ) in a warmer world, CPO should facilitate sustained dialogue between researchers and stakeholders. These conversations are needed to develop trust and to build an understanding of what the stakeholder community actually needs. No stakeholders participated in the AQ breakout group discussion at the Workshop. In particular, those who study AQ in a warmer world need to connect better with human health researchers. Climate data sets are not necessarily easily accessible to the health impacts community.

Detailed atmospheric composition and chemistry need to be included in longer term forecasting models. Most of the current focus at NOAA is on developing short-term weather and air quality forecasts (e.g., out to 48 hours). AQ forecasts that look at seasonal and interannual variability and changes in extreme events for the next several decades are needed. These developments will require better coordination between the weather and climate forecasting communities, both within NOAA and also across the Federal agencies and academic institutions.

More research is needed to separate the impacts of physical changes in a warmer world (e.g., precipitation, cloudiness, boundary layer height, vertical transport, etc.) versus changes in air quality. This is particularly important for determining how human populations will be affected by degraded AQ in a warmer world. In regulatory agencies such as EPA, most of the effort is on developing emissions quantification and control strategies, with less attention paid to a broader understanding of factors that aren't necessarily under local control (larger scale climate changes, for example).

Climate Information Needs: The climate data needed to understand AQ impacts in a warmer world will depend on the individual stakeholder's perspective. Depending on the spatial and temporal scales of relevance, the needs for specific climate and air quality information may vary greatly. AQ models need to use the same meteorological datasets employed by physical climate predictions. AQ models often use reanalysis or nudged meteorological datasets that work well for short-term AQ predictions, but which are inconsistent with longer term climate studies.

There is a critical need for sustained observations of chemical species that contribute to AQ at the same time and place as meteorological measurements. More data are needed in particular for particulate matter, including particle size, chemical composition, and radiative properties. Most long-term AQ datasets record only near-surface ozone concentrations and the mass of particulate matter less than 2.5 microns. More field work is needed to provide detailed snapshots of AQ in different regions over time. Many model

Small breakout group discusses Extreme Heat and Air Quality, led by chair Greg Frost. Photo Credit: Courtney Byrd.

parameterizations are based on ideal conditions which may not be representative of a warmer world with more extreme heat events. Collecting more data for different conditions can test the uncertainties in model algorithms.

More research focus is needed to build a process-level understanding of AQ and its relationship to changes in meteorological variables in a warmer world (particularly heat-related changes in biogenic and anthropogenic emissions, atmospheric chemistry, physical processes, and large-scale transport). Many current AQ models are tuned, which means that their predictive capability to understand longer-term changes under extreme heat conditions will be limited. Improved model resolution and flexible model grids are also needed. Because of non-linearities in chemistry and physics and the heterogeneity of emissions sources, air quality predictions and the consequent impacts on human health will vary greatly at relatively fine spatial scales.

The use of innovative methods may greatly increase the amount of observations and improve the analysis of AQ impacts in a warmer world. Next-generation geostationary and polar-orbiting satellites will likely provide a wealth of new observational data over the next few decades. Low-cost sensors could drastically increase the amount of data available in urban areas, assuming issues with the accuracy and precision of these sensors can be managed. Machine learning/artificial intelligence analytical techniques could help researchers deal with vastly larger datasets than have previously been employed.

2.2.3 Urban

Chair: Ashish Sharma
Rapporteur: Caitlin Simpson

Critical problems: The group's discussion identified a number of critical problems related to extreme heat impacts for city infrastructure (power grid failure) and health (heat-related mortality, worsening air quality, and reduced access to clean water), highlighting hyper-local hotspots and repeated extreme heat events as a significant threat. Lack of information related to extreme heat impacts hinder cities from making informed decisions, such as - where to install cooling centers to optimize access and avoid grid failure; or where to design urban green infrastructure to make the most of the limited resources and investments, or how to invest in innovative ways to capture waste heat (transportation, AC).

Challenges: The group acknowledged that *one urban solution does not fit all urban areas* and recognized there is a need for coordination between scientists and decision makers across governance/jurisdiction levels (city, state, federal). Challenges remain in answering questions such as: *What data do cities have? What climate datasets are available? How can a city benefit from all the vast datasets at different spatial and temporal scales? Which dataset is most useful for which urban application.*

The group highlighted that it is difficult to know what resources cities do or do not have access to, and suggested a city's readiness level to extreme heat events will be impacted by a number of factors, including decisionmaker's ability to make strategic resource choices in light of a range of uncertainties (e.g. two versus four heatwaves per season). Most cities do not have the workforce capacity to apply raw data and climate model output to resource management decisions. Raw data would be more effectively used if translated into preparedness and hazard mitigation information.

Climate Information Needs: To meet these information needs, the group identified climate information and approaches to better deliver climate information to urban stakeholders. Suggested relevant information spanned the weather to climate timescale and includes: Frequency of high heat events (e.g. how many days above 90 degrees); Mean maximum heat; Heat humidity; Downscaled CMIP data (*noted as ambitious); Regional-scale integrated simulations (e.g. socioeconomic development, climate, infrastructure, + RCP). Approaches encompassed an iterative approach with decision-makers. The group envisioned 1) a type of community-research partnership, that combined climate data with scenario planning in an integrated systems approach with continuous dialogue; and 2) development of a type of consumer report, with guidance for decision-makers of different climate information, models, projections, data that had been developed iteratively through surveys and feedback.

Small breakout groups with representation from the Earth System Science and Modeling Division, Climate Society and Interactions Division, the ESSM Council, the New York City Mayor's Office, and the external academic community discuss Extreme Heat and Urban needs. Photo Credit: Courtney Byrd.

2.2.4 Marine Heat Waves, Fisheries & LMR

Chair: Patrick Lynch
Rapporteur: Roger Griffis

Marine heat waves (MHWs) are prolonged anomalously warm water events in specific areas that can cause devastating impacts to marine life and the people, businesses and communities that depend on them. MHWs appear to be increasing in frequency and duration in some regions, and this is expected to continue with increasing ocean warming. Efforts to track, forecast and project MHWs are not well developed, although this is an area of active research and modeling. There is high and growing demand for additional information to understand, prepare for and respond to MHWs.

Critical Problems: MHWs can cause significant impacts to marine ecosystems and wide range of related sectors including marine dependent industries (e.g., fisheries, tourism, shipping, energy), marine resource management (impacts on fish stocks, fisheries, habitats, protected species, protected areas), local communities/economies (e.g. tourism, recreation, fisheries), and public health (e.g., toxic algal blooms).

Climate Information Needs: To help prepare for, respond to, and recover from MHWs decision-makers need:

- Early warnings and longer term projections of MHWs (timing, magnitude, duration, location in 3D, and frequency)

- Information on risks/likely impacts to marine resources and related sectors
- Information on how to prepare and respond to reduce impacts
- Information on past events to aid in recovery planning

There are some existing monitoring, research and modeling efforts that could help address these needs (e.g., NMME, El Nino forecasts, ocean monitoring and modeling efforts etc). However, to address these needs, additional efforts are needed to:

- Understand the drivers/origins of MHWs
- Develop robust MHW early warnings/forecasts and longer term projections (timing, magnitude, duration, location in 3D, and frequency)
- Understand risks/likely impacts to marine resources and related sectors
- Identify how to prepare and respond to reduce impacts
- Assess past events to aid in recovery planning

2.2.5 Agriculture, Forestry, Wildfires

Chair: Danica Lombardozzi
Rapporteur: Sean Bath

Critical Problems and Information Needs: Extreme heat increases water demand for plants and therefore is closely tied to drought stress. Heat and drought stress can cause agricultural losses and tree mortality, make forests more susceptible to secondary pathogens, and increase the probability of wildfires. Decision makers need to answer specific questions to make practical cost/benefit decisions about how to best manage and mitigate the impacts of extreme heat for agriculture, forests, and wildfires.

The agricultural community has already sustained significant economic losses due to extreme heat. The community will benefit from improved seasonal forecasts of the intensity and frequency of extreme events to aid in decisions related to management practices and infrastructure. For example, seasonal forecasts delivered in the spring can help farmers to make decisions before planting, allowing them to decide the appropriate crop variety or cultivar for planting and decide whether or not to till the soil (tillage contributes to water loss). Forecasts throughout the growing season can help farmers adjust additional management practices, such as irrigation amount or frequency, prior to extreme heat episodes. Long-term (multi-year) outlooks are also useful for the agricultural community, as it can aid managers in making decisions about changing infrastructure (e.g., whether to install new irrigation lines or invest in air conditioning for animal facilities).

Within the forestry community, the indirect impacts of extreme heat are quite important. For example, extreme heat can make trees more susceptible to secondary pathogens, such as the pine bark beetle. The UDSA’s Southeast Climate Hub developed a tool for predicting pine beetle outbreaks that has been successful at mitigating the impacts of beetle outbreaks. This tool integrates information about the current distribution of beetles (at the county-level), the type of vegetation, and spring air temperature. Extreme heat can also increase plant water use, decreasing water availability for downstream communities.

One of the larger impacts of extreme heat in the forestry sector is the potential for wildfire. Accurate wildfire predictions are needed to determine how and where to allocate resources to best protect life and property. Seasonal forecasts are necessary for determining how to allocate annual resources, like funding to fight wildfires and where to focus mitigation efforts. Daily and weekly forecasts are also necessary to determine where to station fire crews to expedite rapid responses.

Stakeholders are not always able to get relevant information to make decisions from current outlooks. This is in part because scenarios with large economic consequences create a demand for information even when the probability is low or uncertainty is high. Low probabilities mean that information is not always provided by the physical science community. On the other hand, there is a wealth of information provided by the physical science community, although the data is not always accessible to the decision makers (either not publicly available, or not available in a format that is useful/usable). Two key actions can help to reduce this gap. First, there is a need for more conversions so that the physical research community can better understand how to make information and data more usable for end-user requirements. CPC is working toward this by holding stakeholder meetings (e.g., over the past two years). Second, there is a need to develop training and capacity across organizations/agencies to teach stakeholders how to most effectively use existing tools.

Agriculture, forestry, and wildfire stakeholder communities would like better access to improved forecasts for several variables, including integrated root-zone soil moisture, snowpack, temperature on seasonal timescales, and the frequency and intensity of extreme events, as well as confidence in forecasts. Sophisticated users are able understand uncertainty in forecasts and are able to incorporate it, for example, into insurance models. However, it can be difficult to communicate practical relevance of forecasts, especially those with high uncertainties, to other users and more broadly, the public. Training should be directed toward sophisticated users, who can then become a bridge to communicate with their peers. The physical science community should try to present information as analogues to past events (e.g., this summer will be as hot and dry as 2012), as this contextualizes events within the experience of the stakeholder group.

3.0 Current Research: Capabilities, Highlights, and Gaps

3.1 Keynote Talks

3.1.1 Extreme Heat and Air Quality, Gregory Frost;
NOAA OAR Earth System Research Lab (Presentation Slides)

More frequent and longer episodes of extreme heat will stress populations by exacerbating poor air quality resulting from increased near-surface ozone (O_3) and particulate matter (PM). NOAA's mission to protect lives and property provides the mandate for OAR's Labs and Programs to maintain and improve their capabilities to measure, understand, and make projections of how extreme heat affects air quality. CPO/ESSM can help lead these efforts, by convening the expert community, supporting research, and communicating science to stakeholders.

U.S. air quality improved significantly beginning in the 1970's due to the Clean Air Act and subsequent regulations. But recent monitoring data suggest a reversal of national pollution trends, and many Americans still live in areas that don't meet current regulatory standards for O_3 and PM. Poor air quality is an increasingly critical issue in many parts of the world and is a leading cause of global illness and mortality.

Observations from recent decades demonstrate that air quality is worse during heat waves. Air pollution leads to higher human mortality during heat waves, compounding the effects of extreme temperatures. An extensive body of research demonstrates that near-surface O_3 and PM have complex responses to meteorological changes in a warmer world, which affect precursor emissions, atmospheric chemical formation reactions, and the dynamical and physical processes that transport and remove these pollutants (*figure below demonstrates these relationships schematically for O_3*).

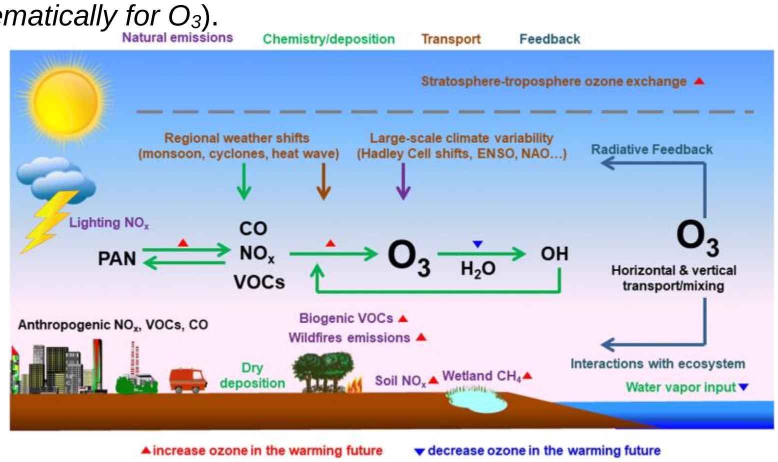


Figure 1. reprinted from *Lu et al., Current Pollution Reports, 2019.*

Earth-system and chemistry-climate models predict that by the mid-21st century:

- Warmer temperatures will result in longer episodes of high near-surface O_3 across much of the continental U.S., assuming anthropogenic precursor emissions remain constant;

- U.S. near-surface O_3 maxima will decrease if anthropogenic precursor emissions decline, and increase if emissions remain at present-day levels;
- Wherever anthropogenic precursor emissions decrease around the world, near-surface O_3 will *decrease* more on heat wave days than non-heat wave days, while O_3 will be *higher* during heat waves compared to non-heat waves wherever precursor emissions remain constant or increase;
- Biogenic emissions from natural vegetation and managed landscapes will tend to increase in a warmer world, providing more O_3 and PM precursors regardless of how anthropogenic emissions change.

3.1.2 Cause of the Summertime Warming Hole: Implication for Heatwaves over the US Heartland, Marty Hoerling;

NOAA Earth Sciences Research Lab (Presentation Slides)

Background and Preliminary Findings The experience of low-frequency temperature variability and change over the U.S. presents a special challenge (see Fig. 2), having for instance a spatial structure quite different and more complicated than that occurring over Europe. Christidis et al. (2015) found that European summer temperatures continued to warm post-2003, a year when devastating heat affected Europe. A substantial further shift of the summer temperature distribution toward higher values ensued. They also found that a hot summer event that had a 1-in-50 year return period in the early 2000s was now estimated to have a 1-in-5 year return period owing to human-induced warming..

The Christidis et al. approach can be viewed as providing a “nowcast” for the likelihood of a heat wave. As a prelude to anticipating the likelihood of US heatwaves, one must thus first explore how extreme heat wave risks have evolved over the U.S. by placing them into a context of observed historical variability since about 1900. One might doubt whether the European experience and their diagnostic results are generally applicable to the US Heartland, especially for summer heat waves, in light the fact that most of the central U.S. has experienced neither a long-term rise in daytime maximum temperatures, nor a tendency of decades since 2000 to be particularly warm compared with the 20th Century (see Fig. 1, left).

The lack of daytime summer warming in the US Heartland can be physically reconciled with the increase in precipitation (Fig 1, right). The cause for the summertime warming hole is thus intimately linked with the cause for the increased rainfall. Our suite of model experiments indicates that neither a strong wetting nor a daytime cooling is part of the model’s global warming signal. However, a few samples drawn from our large ensemble simulations revealed that when Central US rainfall increases on centennial scales (of the magnitude observed -a rare model occurrence), a warming hole-like pattern likewise emerges. Our analysis is ongoing and seeks to broaden its approach to a multi-model diagnosis to establish robustness and confidence in interpretation.

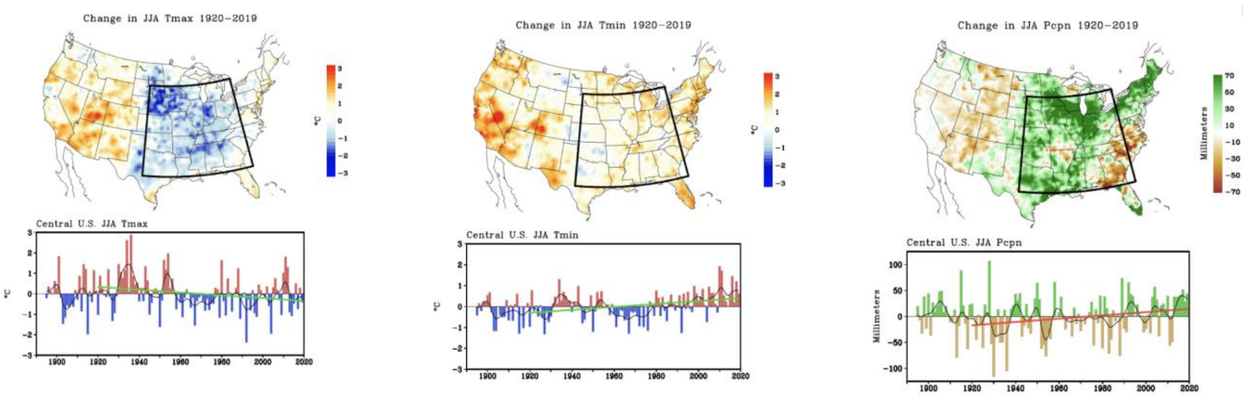


Figure 2. *The 1920-2019 linear trends (total change) of summer maximum surface air temperature (°C, left), minimum surface air temperature (°C, middle), and precipitation (mm, right). The time series (lower panels) are for the 1895-2019 summer departures averaged over the central U.S. outlined by the black box. Departures are relative to a 1895-2019 mean, and the 1920-2019 linear trend is shown by the superposed line.*

3.1.3 Climate Modeling Capabilities for Extreme Heat and Impacts, Tom Delworth;

NOAA OAR Geophysical Fluid Dynamics Lab (Presentation Slides)

We describe the mission and capabilities of NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) as it relates to Extreme Heat and Impacts. GFDL's mission focuses on the development and use of leading edge numerical models of the climate system to advance NOAA goals on understanding and prediction.

Over the last several years GFDL has developed a new state of the art suite of unified climate modeling tools to address a wide range of climate variability, predictability and change topics. The new modeling components (AM4 atmosphere, MOM6 ocean code, SIS2 sea ice, and LM4 land model) provide powerful new capabilities for studies of climate variability, predictability and change, including extreme heat. In this talk, we focus on the application of one part of this new suite for issues related to extreme heat.

The new GFDL seasonal to decadal prediction system is called the "**S**eamless system for **P**rediction and **EA**rth system **R**esearch" (SPEAR) and is being developed for unified climate predictions and projections from the seasonal to decadal to multidecadal time scales. On the seasonal time scale this model will be part of the North American Multimodel Ensemble (NMME). Research has been conducted with earlier GFDL models to investigate predictability of summer temperatures, including extreme heat, especially with respect to the role of initialization systems. This research has highlighted the impact of stratospheric initial conditions on seasonal temperature predictions.

On decadal scales GFDL modeling studies have examined the impact of decadal scale oceanic variability on heat waves over North America and have demonstrated a strong impact of Atlantic sea surface temperature anomalies on North American heat waves. On multidecadal scales we have conducted large ensembles with models, including SPEAR, to investigate the changing likelihood of extreme heat events in response to radiative forcing changes.

The SPEAR system will be used for studies of changes in extremes of heat and hydroclimate, both for seasonal to decadal prediction as well as in response to changing radiative forcing over the coming decades. It is anticipated that model output from large ensembles of SPEAR climate change simulations will be made publicly available for community based research.

3.1.4 Predictability of marine heat waves and impacts, Mike Jacox;

NOAA Southwest Fisheries Science Center; NOAA OAR Earth System Research Lab
(Presentation Slides)

Given the potential for marine heatwaves (MHWs) to profoundly disrupt marine ecosystems, the question naturally arises of whether these events might be predictable. Advance warning of MHWs, whether it be for the onset of anomalies warming or its evolution thereafter, would enable ocean managers and other stakeholders to be more proactive in their decision making. Since MHWs represent one tail of the ocean temperature distribution, MHW predictability is closely related to predictability of ocean temperature anomalies more generally, which has received more attention. Predictable responses in regional sea surface temperature (SST) are linked to large scale modes of climate variability; in particular, El Niño events are often associated with warming in much of the Pacific and Indian Oceans, including off the US west coast. The mechanisms that drive this warming include atmospheric teleconnections, which alter winds and surface heat fluxes, and oceanic teleconnections, which alter the water column structure through coastal trapped wave propagation, both of which may impart predictability. A range of other mechanisms for physical predictability have been explored, including the influence of ocean currents, Rossby waves, reemergence, and persistence. In some cases they have been shown to impart forecast skill for ocean warming; however, the robustness of these prediction mechanisms and the ability of forecast systems to capture them remain poorly understood. Thus, the questions of how predictable MHW are, what mechanisms underlie predictability, how well MHW are represented in models, and how we can close the gap between predictability and forecast skill remain important areas for further research. And, finally, if we are able to forecast MHW with some skill, how will these forecasts be used by fisheries managers and other decision makers?

3.1.5 Air Quality, Climate, and Health, Susan Anenberg;

George Washington University (Presentation Slides)

Air pollution is among the leading public health risk factors globally. Climate change is an increasingly important driver of air pollution and associated health outcomes. Two key sources of air pollution that are affected by climate change include fine particulate matter from wildfires and airborne soil dust. The Fourth National Climate Assessment reported that climate change is expected to cause substantial damages to multiple U.S. sectors, with the largest risks in 2090 related to extreme temperature mortality, labor productivity decline, and coastal property loss. Compared to these projected national-scale climate impacts, estimated dust-related health damages of $47 billion per year for four Southwestern states rank 4th, and is approximately double the ozone-related health impacts. In addition, modeling studies show that the contribution of wildfire smoke to total PM2.5 and associated mortality in the U.S. may grow substantially in the future without greenhouse gas mitigation. The strong relationship between PM2.5 exposure and mortality indicates that improving understanding of climate change impacts on PM2.5, including from dust and wildfire smoke, is critical to assessing the health damages from climate change. Modeling the air quality and health impacts of climate change is complex, and requires information about emissions, future meteorology, interactions between climate and air pollution levels, relationships between air pollution levels and health outcomes, and the economic value of those health outcomes. The complexities expand when considering environmental and institutional contexts, as well as social and behavioral contexts. Impacts of climate change on global air pollution remain unknown, yet may become dominant in some areas in the future. Future needs include additional information on drivers of air pollution emissions and exposure (e.g. future temperature, precipitation, humidity, and wind speeds; climate influence on land use; urban heat island effects; interactions between people, climate, and natural systems), as well as collaborations between climate scientists and health researchers.

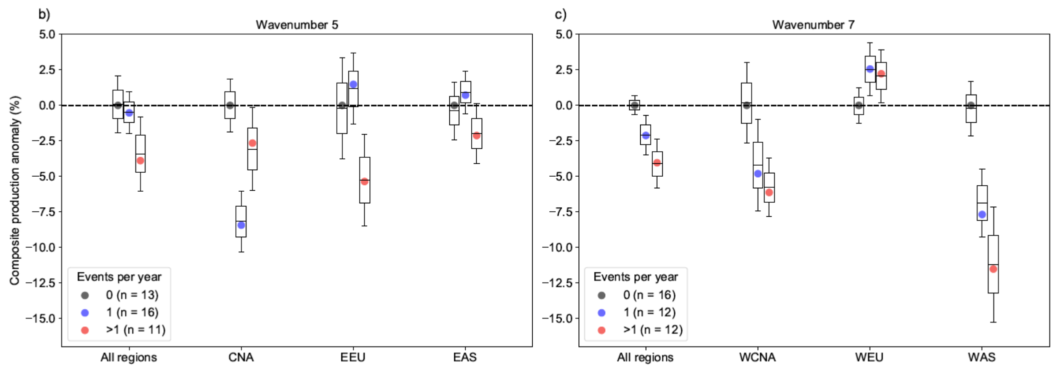
3.1.6 Extreme Heat in a Changing Climate, Radley Horton, Colin Raymond, and Kai Kornhuber;

Earth Institute, Columbia University (Presentation Slides)

The Consortium for Climate Risk in the Urban Northeast (CCRUN), a NOAA RISA Project, has been working with vulnerable communities, municipal governments, and electrical utilities to develop temperature projections tailored to decision-maker needs. This work has resulted in extensive publications in both the climate science literature and on the public health impacts of extreme temperatures by city, age group, type of preexisting health condition, and based on different adaptation assumptions. Increasingly, CCRUN is moving beyond 'temperature only' to consider correlated extreme events and their societal impacts. A recent NSF and NOAA-CCRUN funded workshop http://extremeweather.columbia.edu/workshop-on-correlated-extremes/) divided correlated extremes into categories, including: 1) **multi-variate**, such as high temperature in combination with high humidity, and 2) **concurrent**, such as simultaneous heat waves in multiple agricultural breadbasket regions.

Multi-variate: CCRUN's stakeholder work informed us that humid heat projections are often more useful than 'temperature-only' projections. The resulting research motivation has led us to realize that some parts of the world, such as the coastal Persian Gulf and parts of South Asia, are already exceeding or approaching wet bulb temperatures of 35C, which are thought to represent a survivability threshold. Furthermore, we find robust upward trends over the past four decades globally in lower but nevertheless extremely dangerous wet bulb temperatures such as 27C, 29C, and 31C. We propose a combination of dynamical and lower boundary condition explanations for the most extreme wet bulb temperatures, with sea surface temperatures (SSTs) looming particularly large. Indeed, we report recent SSTs in excess of 35C in the Persian Gulf, which supports the idea that the station-based extreme wet bulb temperatures have a strong physical underpinning, rather than representing instrumental error.

Concurrent: We identified that when the summer midlatitude circulation features highly amplified wave-5 and wave-7 patterns, there is a greater tendency for the ridges and troughs to become 'locked' in space. Furthermore, we identify preferred longitudes for the ridges (and troughs) to occur, and link the 'locking' of the ridges to simultaneous extreme heat events in multiple regions. Finally, we find that during summers in which two or more weeks were spent 'locked' in the high amplitude wave-5 and wave-7 state, yields of major food crops tend to be lower (Figure 1; Kornhuber et al. 2019).



References
Kornhuber, K., D. Coumou, E. Vogel, C. Lesk, J. Donges, J. Lehmann, and R.M. Horton. Circumlobal
Rossby waves enhance risk of simultaneous heat extremes in major breadbasket regions. *Accepted, Nature Climate Change.*

3.1.7 Extreme Heat in Cities: Synergies between urban heat islands and heat waves, Dan Li;

Department of Earth and the Environment, Boston (Presentation Slides)

Urban areas are generally hotter than the surrounding vegetated rural land, which is the well-known urban heat island effect. The urban heat island effect exhibits strong temporal variabilities. In particular, a number of recent studies have shown that the urban heat island effect, defined as the urban-rural temperature difference, tends to become stronger under heat waves (i.e., abnormally hot periods that last several days). However, a few other studies did not find synergistic interactions or reported insignificant interactions between urban heat islands and heat waves (see Figure 1 for a schematic of the debate). Addressing this debate is critical since the interactions between urban heat islands and heat waves have important implications for human health, electricity demand, air quality, ecosystem services, etc. It can also deepen our understanding of land-atmosphere coupling mechanisms under heat waves over heterogeneous terrain. In this presentation, some observational evidence for synergistic interactions between urban heat islands and heat waves is presented first to illustrate the physical processes that might contribute to such synergistic interactions, including the unique roles of anthropogenic heat flux and urban heat storage and the unequal response of urban/rural vegetation to heat wave conditions. Then, urban climate modeling within the earth system modeling framework is discussed, with a focus on the urban canopy model recently implemented into the Geophysical Fluid Dynamics Laboratory (GFDL) earth system model. The capability of the urbanized GFDL earth system model in capturing the continental-scale urban heat island patterns and their responses to heat waves is highlighted. The presentation further discusses the use of attribution methods to quantify the contributions of different biophysical processes to the simulated urban heat islands and their interactions with heat waves. Future needs in terms of urban model improvements, more accurate model input data, and better observational data for model validation are also discussed.

3.1.8 Extreme Heat in Alaska and the Arctic, John Walsh;

Alaska Center for Climate Assessment and Policy, University of Alaska, Fairbanks (Presentation Slides)

Strong warming of the Arctic over the past several decades has led to extreme and, in some cases, unprecedented heat events in Alaska and the Arctic. Record high daily and monthly air temperatures have become increasingly frequent in all seasons. Marine heat waves in the past few years have also occurred in the Bering Sea and Gulf of Alaska, where an attribution study has shown that the record high surface and subsurface water temperatures would not have occurred without anthropogenic warming. The warming has been accompanied by striking reductions of sea ice cover in the waters west and north of Alaska, with corresponding feedbacks to air temperatures, especially during autumn and winter (Figure 1). Impacts of the extreme heat occurrences include melt events covering nearly the entire surface of the Greenland ice sheet as well as more frequent and widespread algal blooms in subarctic seas. Toxins in these blooms and in the warmer waters have been detected in marine mammals (whales, walrus, seals, sea lions) and seabirds in the offshore waters from the Gulf of Alaska in the south to the Chukchi and Beaufort Seas in the north. Other impacts of the extreme heat include an increasing frequency of severe wildfire years, which produce widespread smoke events and extremely unhealthy air quality for weeks during the summer. More frequent freezing rain events during the cold season have led to increased mortality of grazing wildlife as well as travel hazards for humans in Arctic communities. Model projections indicate that the numbers of hot days meeting various temperature thresholds will increase several-fold over the remainder of the century. While the increase in heat events is a consistent signal in climate model simulations of the 21st century, there is considerable uncertainty with regard to the timing, spatial scale and nature of the impacts. These impacts pertain to marine and terrestrial ecosystems, the fisheries and tourism industries, human health, and the consequences for weather and climate in middle latitudes.

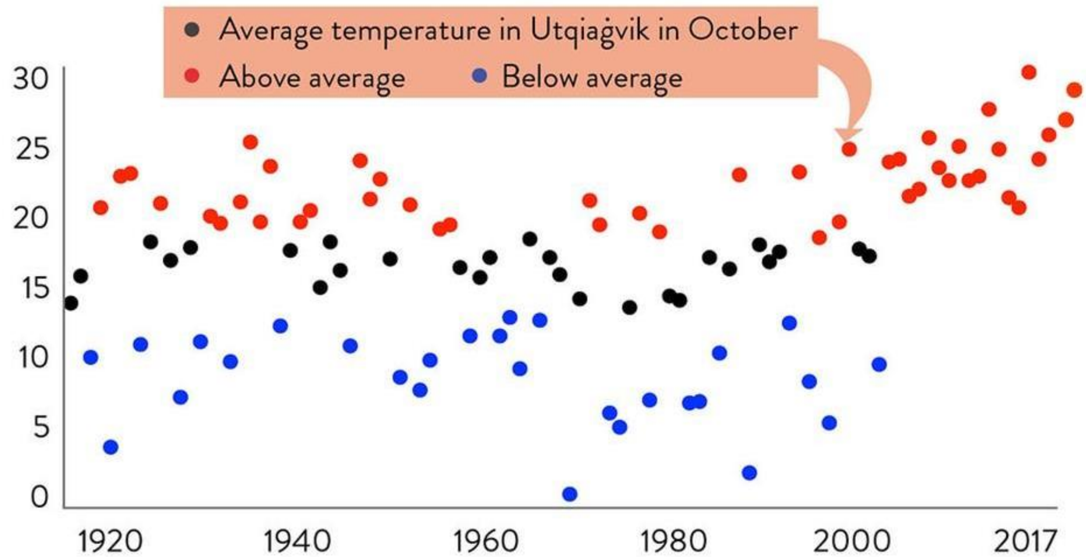


Figure 1. October temperatures (°F) at Barrow (Utqiagvik), Alaska, 1920-2019. Upper, middle, and lower terciles are indicated by red, black and blue, respectively. Figure by Richard Thoman, Alaska Center for Climate Assessment and Policy, University of Alaska, Fairbanks.

3.2 Small Break Out Group Discussion

3.2.1 Applications and Products: Air Quality, Urban, and Health

Chair: Vaishali Naik
Rapporteur: Monika Kopacz

The group summarized key points from Day 1 conversations: Dialog between scientists and stakeholders is needed and there is a need for better coordination between weather and AQ forecasting communities. The most critical data will be dependent on the stakeholder, but in general there is a need for sustained observations of atmospheric chemistry, further fieldwork efforts, more large-scale process understanding, improved model resolution, and new observational technology (e.g. low cost sensor) considerations.

Existing Capabilities
Observations: While Air Quality networks exist in several cities, some data is perhaps no longer representative and/or reliable (have been placed a long time ago). Observations of O_3, $PM_{2.5}$, CO, and SO_2 are most reliable. Air quality variables are co-located with temperature/wind speed and other meteorological fields (e.g. in Houston) in very few areas and these observations cannot be moved. Therefore, the influence of people moving out of city centers to suburbs over time is not captured. In general, there are a lot of weather observations, but NWS station data are not being used for reasons outlined below. Low cost sensors are increasing in this field, but it is not clear how much value there is in using them and how they can be used. It may be worth investing in trying to merge low cost network sensors and high quality monitors (which do not provide information on spatial variation).

Modeling and Process-level understanding: For urban climate/weather fields, scientific understanding and forecasting capabilities are pretty good. Generally, temperature is a better modeled quantity than precipitation or humidity. High resolution tools are available as research tools; they are not operational. NOAA's HRRR model has urban capabilities, however, a major gap here is that it is not coupled to any chemical models. However, WRF-Chem, whose WRF core is related to HRRR, is a very useful model for exploring urban air quality issues under conditions of extreme heat. In terms of process understanding, it is well established that heat, health, and AQ are related. While we understand single variable relationships (e.g. Air Quality response to Stagnation), much less is known about multivariate outcomes (e.g., response of Air Quality to concomitant changes in multiple meteorological fields driving changes in emission sources and sinks).

Gaps and Opportunities for Future Research and Partnership: A major gap is that models that simulate extreme heat at high resolutions are **not coupled to atmospheric chemistry models.** Additionally, regional models that do include this coupling do not include a representation of the urban canopy environment. Similarly, global models that include the coupling of meteorology and chemistry are not run at resolutions high enough to be useful for predicting human exposure to heat and air quality (e.g. large differences between surface and roof tops for both heat and Air Quality). Furthermore, factors that influence Air Quality (Urban Humidity) are not well predicted (large gap). This level of information is crucial for what stakeholders need and for **mitigation.** For example, if cities invest in building a park, how will this improve Air Quality? While a detailed representation of urban morphology in global models is not important for predicting heat and Air Quality over large spatial scales, they are the best tools to predict climate/Air Quality over multi-decadal to centennial scales.

There is a need for **data repositories** that would make both weather and AQ data more accessible and quality controlled and could be utilized in a way that is useful for stakeholders. Participants expressed that those repositories exist, but it is still hard to find the data and it is hard to use. There has been some effort for ozone data (a volunteer effort). There is a need for a service similar to **Copernicus/CAMS service** which would streamline access to data across different agency platforms, but which would only work if all the agencies are forced to make it accessible and stored on a common platform. Additionally, public-private partnerships could be encouraged to develop such data repositories.

The lack of a consistent collection of **health data** to predict health outcomes, as well as access to existing data is extremely challenging. An effort similar to NASA/HAQAST to connect health and climate people could be helpful. Exposure (where are people are going) is a key consideration, in addition to the variability of heat and air pollution throughout the city (health issues include asthma, cardiovascular disease, pre-term and low-weight birth).

Highlighted Opportunities:
Advance comprehensive modeling capability (e.g., such as earth system models that represent atmosphere-biosphere interactions necessary to capture changes in pollution sources and sinks in response to climate change) as well as increase resolution to consistently predict urban climate, impacts on Air Quality, and health impacts from both climate and Air Quality.

- Questions include *how do synoptic scale conditions, favorable for the formation and build-up of pollution (e.g., stagnation), change in a warmer climate in the future?*
- Coupling of urban climate and chemistry modeling is needed to address *How extreme heat affects AQ, especially at urban and exposure relevant scales?*
- Considering human health impacts, these more episodic (e.g. stagnation event) impacts on air quality, should be considered in combination with chronic human exposures to poor Air Quality.
- Improve prediction of changes in wildfires and smoke with current and future climate – models and forecasts are currently inadequate

Develop more products based on existing NOAA data and model outputs (e.g. CMIP analysis. While predictions of stagnation have been analyzed from CMIP5 simulations, they were decoupled from AQ predictions (as not all models included atmospheric chemistry). Analysis of results from CMIP6 models that have now advanced to include coupling between atmospheric chemistry and meteorology, as well as include some terrestrial biosphere-atmosphere interactions, could provide a more coupled understanding of meteorology-AQ connections (a low hanging fruit).

Improve understanding of Secondary Organic Aerosol (SOA) and $PM_{2.5}$. SOA understanding is still a great challenge (formation, composition, fate), especially in urban areas and more research is needed on surface area, size distribution, composition, hygroscopicity and changes driven by climate, heat, etc to understand the health impacts of $PM_{2.5}$; Improve CMAQ.

The above opportunities could be pursued through interactions among climate and health scientists and stakeholders (similar to NASA/HAQAST), could be facilitated through RISA, CPTs, or Climate Synthesis Teams. Multidisciplinary efforts would yield additional information on impacts and inform planning for resilience: incorporation of multivariable epidemiology for synergistic exposure to heat and air quality (hospital visits for different reasons); quantifying co-benefits of mitigation for heat and air quality, understanding the decision-making context (e.g. Does ozone alert lead to any action?)

3.2.2 Applications and Products: Agriculture, Forests, Wildfire

Chair: Rong Fu
Rapporteur: Sean Bath

Existing Capabilities: The participants of this subgroup identified the following existing capabilities that can be used to provide actionable information to users in agriculture, forests and wildfire sectors:

- The NMME S2S predictions can provide key user relevant indices, such as the Fire Building Up index and Vapor Pressure Deficit, which are strongly needed by users across all three sectors;
- North American Land Data Assimilation System provides soil moisture, runoff and other needed land surface information;
- CPC Seasonal outlooks provide information for droughts and fires;
- Fire models developed by other agencies and academics such as NCAR, DOE and UC-DOE lab collaborative projects.

Gaps and Opportunities for Future Research and Partnership: The main gaps between existing capabilities and users' needs are the capability of the NOAA climate predictions at global and large-scales versus the needs of the stakeholders at regional to local scales, especially for precipitation and temperatures; the uncertainties of the predictions; lack of clear and readily available information about the uncertainties for stakeholders; and the gaps between the information provided by NOAA and the information needed by stakeholders. For example, NOAA climate predictions provide surface temperature, humidity, and rainfall of monthly or seasonal averages, whereas stakeholders need seasonal predictions of fire buildup index, pyrocumulus index, the timing of the peak fire risk, and temperature during corn tassle period in July. Ranchers need to know longer-time projections of heat-waves to protect their cattle. This subgroup has identified the following opportunities:

- <u>Short-term (1-3 years) low-hanging fruits:</u> a) provide actionable information using the NMME S2S predictions. For example, the Build Up Index that shows how dry surface is ripe for fires. This index is now provided by ERA5 and used by Fire Services in Western US and Alaska to position resources. Vapor Pressure Deficit (VPD) is central for fire weather and predict crop yield. Seasonal predictions of these indices are especially needed for planning; b) Provide transparent information about predictability, limits and biases, provide metadata for the NOAA predictions and data products.
- <u>Middle to long-term (3-5 years, 5-10 years):</u> a) Improve fire weather prediction. For example, NOAA Fire Seasonal outlook provides bias corrected predictions and information about peaks of fire risk. b) improve understanding of the influence of ocean-Land-atmospheric interaction on predictability; c) Improve our fundamental understanding of the processes central for surface temperature variability, changes, and extremes. d) Explore climate scenarios that would have profound impacts on society should they occur. For example, determine the probability of the arctic sea-ice recovery, dust bowl to occur again, the possibility that models do not represent the range of the variability, and what climate would be if CO_2 emission is worse than the worst-case scenario.
- <u>Game changer or high-risk/high-return area (i.e., a bold move):</u> a) users identified climate information that could utilize multi-year predictive capability. For example, close partnership with insurance companies to develop risk models, probabilistic prediction for

interannual & decadal with interested partners, compounding extremes research on climate variables affecting fire, impacting agricultural production, citizen science / sensors / drones that could increase observations across space and improve applications for agriculture, forest and fire decisions, and using new technologies and big data approaches: i.e., using high resolution climate model and mapping of the weather, agriculture, forestry and fires to improve early warning systems.

- Mechanisms to engage the external research community: Resume and expand PACE Postdoctoral Fellowships; Co-found projects with stakeholders and foundations; Entrain broad research communities and support skill assessments of multi model ensemble predictions such as NMME for extreme temperature.

Small breakout group discusses research gaps and opportunities, focused on marine heat waves. Photo Credit: Courtney Byrd.

3.2.3 Applications and Products: Fisheries, Living Marine Resources

Chair: Enrique Curchitser
Rapporteur: Todd Christensen

The breakout group on marine ecosystems and fisheries met on day 2 of the workshop on extreme heat to synthesize existing capabilities and possible directions in relation to the challenges facing the marine environment in relation to marine heatwaves. The discussion started with an identification of the impacts and challenges that decision makers will have in relation to marine heat events. Decision makers were identified as including fisheries managers, communities and native tribes. Information that may be relevant for them includes: Forecasting emergence, amplitude and duration of a marine heatwave, its trajectory and spatial extent, projecting frequency of events and post-event analysis.

Existing Capabilities Current capabilities that can be used to address critical problems are

1. Existing observation network including satellite, moorings, autonomous vehicles—gliders, sail drones and Argo.
2. Model products:
    - Nowcasts and hindcasts ocean models
    - Some regions have seasonal forecasting capabilities (e.g., J-SCOPE in the NE Pacific)
    - North American Multi Model Ensemble (NMME), Climate Forecast System (CFS)

Gaps and Opportunities for Future Research and Partnership: However, many gaps remain in our understanding of marine heat waves and their impacts on ecosystems. The group concluded that a better categorization of heat waves will be useful in order to separate more common events (e.g., El Niño) from unusual extreme situations. Furthermore, as the these events become more common, the baseline against which they are measured is changing, necessitating a more nuanced definition of an extreme event. The group also recognized that there is limited mechanistic understanding of how the ocean responds to a heat wave.

Opportunities for further research and connection to relevant stakeholders exist in a broad spectrum of topics beginning with carrying out regular initialized forecasts, from basin- to coastal-scales. Further research is needed into the mechanisms for precursors of marine heatwaves. How do they form? What are the drivers?. Additionally, there needs to be further work on physical-biological interactions and the ecosystem response to extreme events. What are the impacts? What are the socio-economic implications?

The discussion group felt that CPO/ESSM can play a crucial role in advancing the research that addresses the above challenges. In particular, ESSM can play a leading role in supporting improved modeling and prediction capabilities that can ultimately lead to an early warning system. Longer term research involves an assessment of the ecosystem to better understand the adaptive capacity of particular resources. How do species adapt to unusual conditions? Examples are long-lived rock fish vs short-lived forage fish, or highly migratory vs local fish stocks.

The group felt that an opportunity exists in planning for a rapid-response research capability that can deploy observations and models in response to a developing extreme event as a way to carry out integrated process studies that will elucidate mechanisms of drivers and response—physics and ecosystem—to heat waves.

3.2.4 Observations and Datasets

Chair: Russell Vose
Rapporteur: Young-Oh Kwon

Existing Capabilities: NOAA supports sustained observations to monitor and further understand extreme heat. NOAA maintains a variety of observing systems that are relevant in an extreme heat context. For the land surface, examples of major national-scale networks include the Automated Surface Observing System (ASOS), the Cooperative Observing Network (COOP), the Climate Reference Network (CRN), and the Surface Radiation Budget Network (SURFRAD). These networks collect observations at hourly and daily time scales for a suite of elements related to extreme heat, including air temperature and humidity, net radiation, as well as soil temperature and moisture. For the global oceans, the Global Ocean Monitoring and Observing Office sustains the collection of long-term, high-quality ocean observations. From an extreme-heat perspective, relevant data include sea surface temperature and surface currents as well as ocean heat content and transport.

NOAA also has other "observational" assets that complement these land and ocean in situ capabilities. For example, NESDIS maintains satellites that measure parameters such as atmospheric moisture and sea surface temperature, and the World Data Service for Paleoclimatology archives proxy data that can depict long-term variations in particular phenomena such as marine heat waves.

Gaps and Opportunities for Future Research and Partnership: *NOAA can take additional steps in an observational context to advance resilience to extreme heat.* Sustained observational networks should ideally focus on societally relevant observations that ultimately support both science non-science communities. With those principles in mind, CPO and ESSM can further advance research on extreme heat by encouraging:

- Partnerships in proposals, especially for the collection of observations. Urban-scale initiatives are illustrative in this regard; partnering with universities is challenging because the cities may be unable to provide funding, so it would be powerful if NOAA could support such partnerships (even by just providing guidance in lieu of funding).

- The supplementation of long-term, basic observations at existing networks with additional elements related to extreme heat. For example, many networks collect temperature and humidity data, but soil moisture and Wet Bulb Globe Temperature are relatively scarce even though they are highly relevant to heat and health.
- Networks to expand beyond their original mission and/or to collaborate with other networks. For example, strategically aligning the CRN and SURFRAD networks would allow for addressing some questions (e.g., related to the surface heat budget) that cannot be made by either network alone.
- And finally, the prioritization of observations that are tied to specific user communities and the creation and maintenance of datasets tied to specific user groups that have a stake in extreme heat. A unique "user" in this regard is the assessment community, which ultimately has impact on many other downstream users.

The workshop brought scientists, such as those from GFDL and Princeton University pictured here, to discuss modeling needs on multiple scales. Photo: Courtney Byrd.

3.2.5 Modeling

Chair: Yi Ming
Rapporteur: Sandy Lucas

Existing Capabilities: The modeling capabilities available for addressing extreme heat events-related questions are tremendous. The tools range from process-level models, to dynamical/statistical downscaling and regional models (like WRF and WRF-Chem), to global weather/climate models (used for weather forecasting, S2S prediction and climate prediction). In the past, these resources have been employed to produce dataset (such as CMIP6) for the community to examine. The community, in return, contributes to the building of new modeling capabilities by developing model components, a process facilitated by Climate Process Teams (CPTs).

Gaps and Opportunities for Future Research and Partnership: Three major gaps are identified. First, despite the advances in modeling tools, there is very limited understanding of how regional climate responds to climate forcings (or emission scenarios) and feedbacks in the climate system. A prominent example is the "warming hole" over central U.S. Given NOAA's focus on North America, one may want to contemplate the possibility of formulating a research initiative aiming at address how global forcings impact North American hydroclimate (temperature and precipitation). Second, there is a mismatch between users' needs (regional/local-scale) and the research community's offerings (global scale). It remains unclear how to bridge the two sides. Third, the lack of prediction skills at seasonal timescale is a major rate-limiting step in applying weather/climate information to decision-making. CPO/ESSM can play a major role in facilitating understanding (see the first major gap). One promising research question one could ask is whether there are certain climate modes that would rend predictability of certain weather events higher or lower. This seems to be a potentially productive angle through which one can examine the interactions between weather and climate timescales. A specific task for CPO/ESSM is how to make GFDL's model simulations more accessible to the user community. Furthermore, CPO/ESSM could take a lead role in the drive toward engaging community partners in improving NOAA's modeling capabilities.

3.2.5 Predictions and Projections

Chair: Ben Kirtman
Rapporteur: Dan Barrie

Existing Capabilities: A broad array of prediction and projection systems exist, but are not fully utilized, (e.g., S2S, NMME, CMIP).

Gaps and Opportunities for Future Research and Partnership: Opportunities exist to leverage the existing systems:

- Focus Coordinated Process Evaluation of Predictions, Projections within the context of how the predictions and projections are used, building user confidence;
- Develop Predictions of Opportunity;
- Utilize Large-Ensemble Experiments;

Stakeholder engagement remains a challenge. New innovative mechanisms to fund and sustain productive interactions are needed (e.g. multi-institution funding; private sector engagement) at an appropriate funding level (not too diluted). There is a need to develop metrics based on use. For example, what are abrupt changes or critical thresholds that are important to users? **Near-term** (i.e.. low hanging fruit, leveraging on-going activities; 1-3 years) opportunities include: Focused Harmonized Assessment/Analysis and Stakeholder Engagement; Bias Correction (other that model improvement); Using Regional Assessment of Global Models to Feedback on Global Model Development. **Long-term** research questions/opportunities (3-5 or 5-10 years?) include considering *how to develop next generation high resolution prediction and projections? Is machine learning an appropriate re-think?*

Plenary presentations and lightning talks informed the small breakout group discussions. Photo Credit: Courtney Byrd.

3.2.6 Process Understanding and Predictability

Chair: Edmund Chang
Rapporteur: Sukyoung Lee

First, the group discussed what important physical processes are related to the critical problems and user-needs identified in day-1. The group suggested that these include greenhouse gas and aerosols driving the warming trend; large scale atmospheric circulation regimes and persistent patterns, as well as synoptic and subseasonal disturbances that are tied to these large scale circulations; land/atmosphere interactions; ocean/atmosphere interactions; and difference between dry versus moist heat wave events. As to what processes are well understood, the group suggested that the global mean temperature trend appears well understood (apart from the uncertainty related to aerosol climate interactions); impacts of ENSO and certain SST forced teleconnections; as well as the fact that heat waves can usually be predicted several days in advance suggesting that our models are able to capture certain aspects of the synoptic disturbances.

Gaps and Opportunities for Future Research and Partnership: Several members of the group highlighted the importance of trying to carefully assess how models simulate and predict these events by confronting models with observations in detail, and if possible, at a physical process level. Processes that should be better understood include why models could not accurately simulate historical events including the 1930's droughts, the observed pattern in SST trend, and the warming hole over the central US. Most GCMs are still not simulating synoptic scale weather well and these should be carefully assessed and the implications understood. In addition, several participants emphasized the relative lack of observational data to facilitate better understanding, including soil moisture observations at depth (not just surface moisture which can be retrieved from satellite observations) to better understand land atmosphere interactions; and ocean advection data are sparse which inhibits the progress in understanding of marine heat waves. Apart from soil moisture atmospheric interactions, there is also a lack of observations and experiments relating to how vegetation responds to extreme heat; and boundary layer and microphysical processes relating to these events are not well studied nor understood.

As to what NOAA CPO/ESSM can do to advance research, the group suggested several avenues, some of which may not be doable by ESSM itself but may need ESSM to coordinate with other agencies. Observations are essential, and it would be essential to support efforts to maintain continuous climate quality observation datasets, as well as to pull together multiple observational datasets to form a database to facilitate increased effort to confront model simulations with observations. More effort should be focused on supporting detailed process studies confronting models with observations, making use of existing multi-model ensemble databases including CMIP6 (and highresmip which will provide relatively high resolution climate simulations and projections) and S2S and SubX databases. In addition, several participants felt that to improve NOAA models, it is essential to support efforts to make the models available for community use and development, so that more outside groups can make use of and thus help assess the model performance that could lead to more rapid model improvements and improved process understanding.

4.0 Main Outcomes of the Workshop

4.1 Key User Perspectives

Critical problems faced by decision-makers were discussed in key impact areas, including urban, health, agriculture, forest and range working land, and fisheries. All breakout groups highlighted the need to understand future changes in the frequency and intensity of extreme events, as well as better understand the risks of compound extremes and their multivariate or cascading impacts. Information that communicates these risks is needed with adequate lead-times to enable effective preparedness and response (subseasonal, seasonal to interannual scales), mitigation (interannual to decadal scales) and adaptation (multidecadal , 50-100 years). In addition to improved understanding, stakeholders also highlighted the need to improve communication pathways and use of existing climate information (forecast products, tools and data) with users.

4.2. Research gaps

Considering the user needs and existing capabilities in scientific understanding, modeling and observations, the following research gaps are identified:

4.2.1. Modeling

There is a mismatch in the resolution provided and that needed by stakeholder groups. Resolutions provided by global, and sometimes regional, climate models are too coarse to meet user needs. In addition, certain features or components (e.g. Air Quality, Urban Canopy) are not incorporated in, or coupled to, the appropriate model to provide needed information (e.g. Urban - Air Quality, Extreme Heat, Human Exposures). High value information (needed by stakeholders) often has low predictive skill, especially on seasonal timescales, which is a major limiting factor for applying climate information to decision making.

4.2.2. Observations for Process Understanding and Modeling

More observations are needed. Examples given included: at-depth soil moisture, urban humidity, snowpack, ocean advection, vegetation responses to extremes, boundary layer microphysics, net radiation, surface and subsurface fluxes (land-atmosphere; ocean; ocean-atmosphere), and air quality-related variables. Identified observations range from field campaigns, high intensity or rapid response, to global monitoring datasets.

Coupled multidisciplinary observations are needed on similar scales (e.g. air quality and meteorological variables) under different conditions to improve process understanding and modeling. Efforts such as these would be critical to test current model parameterizations that are based on ideal, rather than real-world, conditions, and also important to further understanding of compound or multivariate effects.

Emerging observations need to be considered. For example, low cost sensors, citizen science, UAVs, and satellites have the potential to provide many more observations; however, reliability and quality are an important consideration. Continuity and consistency with other historical long-term observational records, in many cases, has not yet been established.

4.3. Recommendations for Future Research

Participants conveyed that all components of the R2X value chain/tree need to be strengthened to build a resilient nation. The Earth System Science and Modeling Division, in partnership with the Climate Society and Interaction Division, is well poised to bring the strengths of each program to bear on responding to user-identified information needs.

ESSM Council Members chaired wrap-up discussions on Days 1 and 2 of the workshop.

Photo Credit: Courtney Byrd.

4.3.1. Paths forward for the Earth System Science and Modeling Division

ESSM programs including CVP: Climate Variability and Predictability; AC4: Atmosphere Chemistry, Carbon Cycle, and Climate; MAPP: Modeling, Analysis, Predictions and Projections; COM: Climate Observations and Monitoring can work together to consider the following:

Enhance understanding of short term and long term temperature increases (including phenomena: Marine heat waves and Terrestrial heat waves), through modeling, analysis, and field campaigns: This includes examining the predictability of extremes (onset, duration and intensity), including forcings (GHG and aerosols), large scales atmosphere circulation regimes, and synoptic, sub-seasonal disturbances tied to large scale circulations, as well as other earth system processes (e.g. land-atmosphere interactions) impacting predictability. Process studies and existing datasets should be used to confront models with observations to assess how models simulate and predict events (e.g. historical events, warming hole over central U.S., North America hydroclimate). Studies should consider: regional responses to climate/global forcings (or mission scenarios); compound extremes and their multivariate or cascading impacts and feedbacks; and physical-dynamical morphology of marine heat waves and terrestrial heat waves.

Improve models and predictive skill, especially at regional scales, through observational and modeling research: Climate models need to be coupled to chemical models on scales relevant to stakeholders for urban applications in order to study multivariable processes important to heat, health, and air quality. Model improvements that address scale and resolution should be considered. For example, increases to model resolution for regional/local applications including flexible model grids, downscaling, and AI tools.

4.3.2. Opportunities for ESSM Division and NOAA partnerships.

ESSM Division can work with partners including the Climate Society Interactions Division and the National Integrated Heat Health Information System (NIHHIS), within the Climate Program Office, the Weather Program Office within OAR, and OAR labs operating observations networks to pursue a subset of outcomes from the Extreme Heat Workshop.

The workshop provided time during breaks and working lunches for networking and collaboration. Photo Credit: Courtney Byrd.

CSI and ESSM within CPO could foster transdiscipline partnerships to increase resilience to extreme heat across societal sectors. Interdisciplinary, research and collaboration should be promoted across the social and physical sciences communities to harness climate modeling for the translation of geophysical variables to actionable metrics. Examples of opportunities to pursue included: Explore climate scenarios that would have profound impacts on society should they occur - “stress testing” climate models through reconstructions of past extreme events (Chicago heat wave - 1992; Dust-Bowl - 1930s); Improve understanding on critical thresholds for urban infrastructure and habitability limits that account for the impacts of compound extreme events.

Sustained collaborative dialogue among climate scientists, policy professionals, and stakeholders needs to be strengthened to develop useful climate predictions/projections for extremes within the context of how climate information is used and to build user confidence. Emphasis was placed on including transparent information about predictability, limits and biases, and metadata.

CPO and the Weather Program Office (WPO) could address needs at the intersection of the S2S and climate timescales. Partnerships could pursue opportunities to use process studies and existing datasets to confront models with observations to assess how models simulate and predict extreme events. Opportunities exist to utilize existing NOAA data and projects. Examples included: Explore forecasts of opportunities of extreme events by examining weather-climate interactions associated with certain climate phenomena and analyzing GFDL model large ensembles.

CPO in partnership with NOAA labs & centers and other agencies can work to maintain and expand observations to better understand extreme heat processes. Partners could look for opportunities to leverage NOAA-supported observational networks, and support collaborative activities across networks, as well as sustain and supplement extreme-heat related observations such as air quality, or health data. Examples included: adding measurements such as soil moisture and Wet Bulb Temperature, and surface energy budget to sites that currently only collect temperature and humidity data or aligning observational networks, such as the Climate Reference Network and SURFRAD network to address questions that either network cannot address alone. Partnerships could also support the utilization of new observations (including emerging technologies) and field process study efforts to address weaknesses in models specific to applications.

Appendix

A. Agenda

Annual ESSM Community Workshop
2019 Theme: Climate Research to Enhance Resilience to Extreme Heat
November 18-19, 2019; Silver Spring, MD

OBJECTIVE & EXPECTED OUTCOME Engage researchers, users, and stakeholders inside and outside NOAA to identify needs and opportunities for the Climate Program Office, Earth System Science and Modeling Programs (CPO/ESSM) to support climate research to enhance resilience to extreme heat. A workshop report with key ideas from participants to inform CPO/ESSM future research directions and funding priorities.

Day 1 (November 18th): User Perspectives

08:00: REGISTRATION & REFRESHMENTS

08:30 - 9:50: Introduction and Overview; Presentations and Discussions: User Perspectives on impacts of extreme heat
Ben DeAngelo (Chair), Deputy Director, NOAA Climate Program Office

08:30: WELCOME
08:40: CPO AND ESSM OVERVIEW & Q/A
Jin Huang, Division Chief, NOAA CPO ESSM Division

09:10 HEAT AND URBAN
Kizzy Charles-Guzman, Deputy Director, NYC Mayor's Office of Resiliency (Remote)

09:30 HEAT AND HEALTH
Shubahyu Saha, Senior Fellow, Climate and Health Program, Centers for Disease Control and Prevention

09:50 BREAK

10:20 - 12:00: Presentations and Discussions (*continued*): User Perspectives on impacts of extreme heat
Dan Barrie (Chair), Program Manager, Modeling, Analysis, Predictions, and Projections program and Assessments program, ESSM Division

10:20 EXTREME HEAT IMPACTS ON WORKING LANDS
Steven McNulty, Director, Southeast Regional Climate Hub, US Department of Agriculture

10:40 EXTREME HEAT: PRODUCTS & STAKEHOLDER REQUIREMENTS
Jon Gottschalck, Chief/Operational Prediction Branch, Climate Prediction Center, National Weather Service

11:00 OCEAN HEAT WAVES & FISHERIES
Mike Jacox, NOAA Southwest Fisheries Science Center and NOAA OAR Earth System Research Lab & **Toby Garfield**, Director, Environmental Research Division, NOAA Fisheries Southwest

11:20: DISCUSSION & QUESTIONS

12:00: GROUP PHOTO

12:15: LUNCH

13:00 - 14:00: Lightning Talks (3 minute talks)
Hunter Jones (Chair), Climate Health Projects Manager, National Integrated Heat Health Information System (NIHHIS)

Health
- Decision-maker needs identified by NIHHIS, Hunter Jones (NOAA/OAR/CPO)
- Combining heat exposure indices with socioeconomic data to build a heat vulnerability index for the Southeast United States, Howard Diamond (NOAA/OAR/ARL)

Air Quality
- When extreme heat meets with dry spell: how does air quality respond? Yuxuan Wang (University of Houston)
- Potential Impacts of Extreme Heat on Air Quality Forecasting, Rick Saylor (NOAA/OAR/ARL)
- Substantial increase in the joint occurrence and human exposure of heat and haze hazards over South Asia in the mid-21st century, Yangyang Xu (Texas A&M University)
- Land-biosphere feedbacks exacerbate climate penalty on air pollution extremes, Meiyun Lin (NOAA/GFDL, Princeton University)

Monitoring and Observations
- Urban Heat Island Mapping & Modeling Campaigns, David Herring (NOAA/OAR/CPO)
- A Global Monitoring System for Excessive Heat: Summary of Heat Events during Boreal Summer 2019, Augustin Vintzileos (University of Maryland)

Extreme Heat Waves Perspectives
- Temporally Compound Heat Wave Events and Global Warming: An Emerging Hazard, Jane Baldwin (Lamont-Doherty Earth Observatory, Columbia University)
- Understanding future change in heat waves and planetary waves in the boreal summer, Haiyan Teng (NCAR)
- Indoor Heat Waves, Brian Vanthull (NOAA/CESSRST)

14:00 Break

14:15 - 15:45: Breakout Group Discussions & Writing Sessions. Summaries of groups' writing sessions will be included in the workshop report.

Questions for discussion:
- What are the most critical problems for decision makers when it comes to the impacts of extreme heat in a changing climate?

- What climate information is needed?

  Parallel Small Breakout Topics
  Air quality
  Chair: Gregory Frost, NOAA/CSD; Rapporteur: Todd Christenson, NOAA/OAR/CPO

  Agriculture, Forestry, Wildfires
  Chair: Danica Lombardozzi, NCAR; Rapporteur: Sean Bath, NOAA/OAR/CPO

  Urban
  Chair: Ashish Sharma, UIUC; Rapporteur: Caitlin Simpson, NOAA/OAR/CPO

  Health
  Chair: Juli Trtanj, NOAA/OAR/CPO; Hunter Jones, NOAA/OAR/CPO

  Marine Heat waves and Fisheries
  Chair: Patrick Lynch, NOAA/Fisheries; Rapporteur: Roger Griffis, NOAA/Fisheries

15:45 BREAK

16:00 - 17:30: Plenary report out by breakout sessions and Panel Discussion
Ana P. Barros (Chair), Edmund T. Pratt Jr. School Professor of Civil and Environmental Engineering, Duke University

Mark Brusberg, Cheif Meteorologist, Office of Cheif Economist/World Agriculture Outlook Board, US USDA

Anne Hollowed, Senior Scientist, Alaska Fisheries Science Center, NOAA Fisheries

Adam Parris, Deputy Director of Climate Science and Risk Communication, City of NY

Day 2 (November 19th 2019): Research Capabilities, Highlights, and Future Opportunities

08:00: REFRESHMENTS

08:30 DISCUSSION - RECAP of DAY 1

08:40 - 10:20: Presentations: Current capabilities and gaps
Monika Kopacz (Chair), Program Manager, Atmospheric Chemistry, Carbon Cycle, and Climate (AC4) program, ESSM Division

08 40: EXTREME HEAT AND AIR QUALITY
Greg Frost, Research Chemist, and **David Fahey**, Director, Chemical Science Division, NOAA OAR Earth System Research Lab

09:00: WHENCE THE US HEARTLAND WARMING HOLE?
Marty Hoerling, Attribution and Predictability Assessments Team, Physical Science Division, NOAA OAR Earth System Research Lab

09:20 CLIMATE MODELING CAPABILITIES FOR EXTREME HEAT & IMPACTS
Tom Delworth, Senior Scientist, NOAA OAR Geophysical Fluid Dynamics Lab

09:40 PREDICTABILITY OF MARINE HEAT WAVES AND IMPACTS ON FISHERIES
Mike Jacox, Research Oceanographer, NOAA Southwest Fisheries Science Center and NOAA OAR Earth System Research Lab

10:00 DISCUSSION & QUESTIONS

10:20: BREAK

10:40 - 12:20: Presentations: Recent Research Highlights and Gaps
Sandy Lucas (Chair), Program Manager, Climate Variability and Predictability program, ESSM Division

10:40: NEXUS OF EXTREME HEAT, AIR QUALITY, CLIMATE, & HEALTH
Susan Anenberg, Associate Professor of Environmental and Occupational Health and of Global Health, George Washington University

11:00: EXTREME HEAT IN A CHANGING CLIMATE
Radley Horton, Associate Research Professor, Earth Institute, Columbia University

11:20: SYNERGIES BETWEEN URBAN HEAT ISLANDS AND HEAT WAVES
Dan Li, Assistant Professor, Department of Earth and the Environment, Boston University

11:40: EXTREME HEAT IN THE ARCTIC: ICE & SNOW MELT, WILDFIRES, AIR QUALITY & MARINE IMPACTS
John Walsh, Chief Scientist, International Arctic Research Center, University of Alaska

12:00: DISCUSSION

12:20: LUNCH

13:00 - 14:00: Lightning Talks (1-slide) to bring up research highlights
Virginia Selz (Chair), Program Manager, Climate Observations and Monitoring Program, ESSM Division

Land/Land-use Feedbacks

- Extreme heat on the Arctic Tundra and the consequences for greenhouse gas emissions, Colm Sweeney (NOAA/OAR/ESRL/GMD, OOMD)
- How dry soil moisture extremes exacerbate heat waves over the contiguous United States, David Benson (George Mason University)
- Irrigation impacts on humid heat extremes, Nir Krakauer (City College of New York)

Climate Variability and Change

- Detection of anthropogenic influence on a summertime heat stress index: global analysis and U.S. perspective, Thomas Knutson (NOAA/OAR/GFDL)

- Impacts of decrease in extratropical cyclone activity in summer on extreme heat events, Edmond Chang (Stony Brook University)
- The 2012 extreme warm anomaly in the Northwest Atlantic: from understanding to predictability, Ke Chen (WHOI)
- Which El Niño flavors are more important for US West Coast marine warming? Antonietta Capotondi (NOAA/OAR/ESRL/PSD)

Urban perspectives
- Lessons from Workshop on Urban Scale Processes and their Representation in High Spatial Resolution Earth System Models, Ashish Sharma (University of Illinois)
- Extreme heat and coastal urban areas- A perspective on modeling & observations, Prathap Ramamurthy (CUNY City College/NOAA-CREST)
- Elie Bou Zoud

Observational needs
- A NOAA Surface Energy Budget and Aerosol Network for Improving Understanding and Predictions of Extreme Heat Events, Kathleen Lantz (NOAA/OAR/ESRL/GMD)

14:00: BREAK

14:15 - 15:45: Breakout Group Discussions & Writing Sessions. Summaries of groups' writing sessions will be included in the workshop report.

Questions for discussion:
- What capabilities already exist to address critical problems and user needs identified in Day 1?
- What are the gaps and opportunities for further research and partnership?
- What can CPO and ESSM do to advance climate research for resilience to extreme heat?
  - What are the near-term (low hanging fruit, leveraging on-going activities, 1 - 3 years) and long-term (3-5, 5-10 years) research opportunities?
  - What would be a game changer or a high-risk/high-return area to pursue?
  - What are the most effective funding mechanisms (e.g. competitive grants, contracts, prizes, etc.) to engage the external research community to advance NOAA's mission in the climate area?

Parallel Small Breakout Topics
Observations and datasets
Chair: Russell Vose, NOAA/NESDIS/NCEI; Rapporteur: Young-Oh Kwon, WHOI

Modeling
Chair: Yi Ming, NOAA/OAR/GFDL ; Rapporteur: Sandy Lucas NOAA/OAR/CPO

Predictions and Projections
Chair: Ben Kirtman, University of Miami; Rapporteur: Dan Barrie, NOAA/OAR/CPO

Process understanding and predictability
Chair: Edmond Chang, Stony Brook University; Rapporteur: Sukyoung Lee, Penn State University

Applications and Products: **Urban, Air Quality, Health**
Chair: Vaishali Naik, NOAA/OAR/GFDL; Rapporteur: Monika Kopacz, NOAA/OAR/CPO

Applications and Products: Fisheries, Living Marine Resources
Chair: Enrique Curchitser, Rutgers University; Rapporteur: Todd Christensen, NOAA/OAR/CPO

Applications and Products: Agriculture, Forests, Wildfire
Chair: Rong Fu, UCLA; Rapporteur: Sean Bath, NOAA/OAR/CPO

15:45: BREAK

16:00 - 17:30: Plenary report out by breakout sessions and Panel Discussion* (next page)

16:00 - 17:30: Plenary report out by breakout sessions and Panel Discussion*

James W. Hurrell (Chair), Professor and Scott Presidential Chair in Environmental Science and Engineering, Colorado State University

Antonietta Capotondi, Scientist, Physical Sciences Division, NOAA OAR ESRL

Brian McDonald, Scientist, University of Colorado Boulder - Cooperative Institute for Research in Environmental Sciences, NOAA

Xubin Zeng, Agnese N. Haury Chair in Environment, Professor of Atmospheric Sciences, Director of Climate Dynamics and Hydrometeorology Center, University of Arizona

17:30 -17:40: CLOSING REMARKS

November 20th Morning: ESSM Council Meeting - Executive session (Closed)

B. Participant List

Full Name	Institution
Anenberg, Susan	George Washington
Arrigo, Jennifer	USGCRP
Baldwin, Jane	Columbia University
Barrie, Daniel	NOAA/OAR/CPO
Barros, Ana	Duke University
Bath, Sean	NOAA/OAR/CPO
Benson, David	George Mason University
Byrd, Courtney	NOAA/OAR/CPO
Capotondi, Antonietta	NOAA/OAR/PSD
Carman, Jessie	NOAA/OAR/OWAQ
Chang, Edmund Kar-Man	Stony Brook University
Charles-Guzman, Kizzy	New York, City Mayor's Office
Chen, Ke	Woods Hole Oceanographic Institution
Christensen, Todd	NOAA/OAR/CPO
Curchitser, Enrique	Rutgers
DeAngelo, Benjamin	NOAA/OAR/CPO
Delworth, Thomas	NOAA/OAR/GFDL
Deng, Yi	Georgia Tech
Diamond, Howard	NOAA/OAR/ARL
DiBerto, Tom	NOAA/OAR/CPO
Elie, Bou-Zeid	Princeton
Ford, Trent	Southern Illinois University
Frost, Gregory	NOAA/OAR/CSD
Garfield, Newell	NOAA??
Gottschalck, Jon	NOAA/NWS/CPC
Griffis, Roger	NOAA/Fisheries
Hallowed, Anne	NOAA/Fisheries
Hirschberg, Paul	NOAA/OAR/CPO
Hoerling, Martin	NOAA/OAR/PSD
Horton, Radley	Columbia
Huang, Jin	NOAA/OAR/CPO
Huddleston, Amara	NOAA/OAR/CPO
Hurrell, Jim	Colorado State University
Hurwitz, Maggie	NOAA??
Jacox, Michael	NOAA/OAR and Fisheries
Jones, Hunter	NOAA/OAR/CPO
Kirtman, Ben	University of Miami
Knutson, Thomas	NOAA/OAR/GFDL
Kopacz, Monika	NOAA/OAR/CPO
Koster, Randal	NASA
Krakauer, Nir	City College of New York

Lantz, Kathleen	NOAA/OAR/GMD
Lee, Sukyoung	Penn State University
Li, Dan	Boston University
Lin, Meiyun	NOAA/OAR/GFDL
Lombardozzi, Danica	NCAR
Lopez, Hosmay	NOAA/AOML
Lucas, Sandy	NOAA/OAR/CPO
Luo, Lifeng	Michigan State University
Lynch, Patrick	NOAA/FIsheries
McDonald, Brian	NOAA/OAR/CSD
McNulty, Steven	USDA
Ming, Yi	NOAA/OAR/GFDL
Mooney, Kenneth	NOAA/OAR/CPO
Naik, Vaishali	NOAA/OAR/GFDL
Nierenberg, Claudia	NOAA/OAR/CPO
Niyogi, Devdutta	Perdue University
Oleson, Keith	NCAR
Parris, Adam	New York, City Mayor's Office
Patterson, Mike	CLIVAR
Quintana, Amanda	USGCRP
Ramamurthy, Prathap	City College of New York
Russell, Joellen	University of Arizona
Saha,	Center of Disease

Shubhayu	Control (CDC)
Selz, Virginia	NOAA/OAR/CPO
Sharma, Ashish	University of Illinois
Shi, Rui	John Hopkins University
Silva, Viviane	NOAA/NWS
Simpson, Caitlin	NOAA/OAR/CPO
Sweeny, Colm	NOAA/OAR/OOMD
Teng, Haiyan	NCAR
Tillman, Danielle	NOAA/OAR
Trtanj, Juli	NOAA/OAR/CPO
van Oevelen, Peter	GEWEX
vant-hull, Brian	City College of New York
Vaughn, Lisa	NOAA/OAR/CPO
Vintzileos, Augustin	University of Maryland
Vose, Russell	NOAA/NESDIS/NCEI
Walsh, John	University of Alaska
Wang, Yuxuan	University of Houston
Williams, Eric	NOAA/OAR/CSD
Xu, Yangyang	Texas A&M
Young-Oh, Kwon	Woods Hole Oceanographic Institution
Zeng, Xubin	University of Arizona

C. ESSM Program Staff

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Dan Barrie (Program Manager: daniel.barrie@noaa.gov)

D. Acronyms List

AC4: Atmosphere Chemistry, Carbon Cycle and Climate
AOML: Atlantic Oceanographic and Meteorological Laboratory
ARL: Air Resources Laboratory
CI: Cooperative Institute
COM: Climate Observation and Monitoring
CPO: Climate Program Office
CPT: Climate Process Team
CSD: Chemical Sciences Division
CSI: Climate Society Interactions Division
CVP: Climate Variability and Predictability
ECMWF: European Centre for Medium-Range Weather Forecasts
ESRL: Earth System Research Laboratory
ESSM: Earth System Science and Modeling
GFDL: Geophysical Fluid Dynamics Laboratory
GLERL: Great Lakes Environmental Research Laboratory
GMD: Global Monitoring Division
GSD: Global Systems Division
JPSS: Joint Polar Satellite System
LDAS: Land Data Assimilation System
MAPP: Modeling, Analysis, Predictions and Projections
NCEI: National Centers for Environmental Information
NESDIS: National Environmental Satellite, Data, and Information Service
NIHHIS National Integrated Heat Health Information System
NMME: North American Multi-Model Ensemble
NOS: National Ocean Service
NSSL: National Severe Storms Laboratory
NWS: National Weather Service
OAR: Oceanic and Atmospheric Research
OSSE: Observation System Simulation Experiments
PME: Pacific Marine Environmental Laboratory
PSD: Physical Sciences Division
UFS: Unified Forecast System
USCLIVAR: US Climate Variability and Predictability
USGCRP: U.S. Global Change Research Program